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INVESTIGATION OF MESOSCALE METEOROLOGICAL PHENOMENA AS OBSERVED BY GEOSTATIONARY SATELLITE

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ABSTRACT

Satellite imagery plus conventional synoptic observations are used to examine three mesoscale systems recently observed by the GOES-EAST satellite. The three systems are an arc cloud complex (ACC), mountain lee wave clouds and cloud streets parallel to the wind shear. Possible gravity-wave activity is apparent in all three cases. Of particular interest is the ACC because of its ability to interact with other mesoscale phenomena to produce or enhance convection.

ACKNOWLEDGMENTS

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INTRODUCTION

Motion systems in Earth's atmosphere cover a broad spectrum of sizes, from roughly hemispheric down to the very small scales of turbulence. A portion of the spectrum has been called mesoscale (Orlanski, 1975), which for our purposes here may be defined to extend from about 400 km to about 1 km. At the large end of this range are the large storm complexes such as squall lines, and at the small end are the individual cumulonimbus clouds. Thus, the mesoscale encompasses phenomena which produce such destructive events as flash flooding, hail damage, tornados, lightning damage and winds affecting aircraft operations.

The study of mesoscale phemonena, particularly at the small end of the scale, by conventional meteorological observations has been essentially impossible because of the horizontal spacing of observation sites. Surface observations generally are 100 km or more apart and upper-air stations generally are several hundred kilometers apart. Therefore, most mesoscale systems cannot be resolved by the observations.

The weather radar has helped overcome some of the deficiencies of the meteorological observation system and a recent development, the meteorological satellite, has made a tremendous impact. As pointed out by Purdom (1979), the Geostationary Operational Environmental Satellite (GOES) has provided the atmospheric scientist a means to see not only the range of atmospheric systems from the synoptic down to the cumulus scale, but also to see the ongoing interactions between scales. Thus, a variety of mesoscale systems have come to be observed and described in the literature such as ocean, lake and river breezes (Purdom, 1976), arc clouds (Purdom, 1973, 1976; Gurka, 1976) and convective complexes (Maddox, 1980). Despite the differences in resolution, it follows that what is needed at this point are studies which combine satellite observations with radar and other conventional data in order to gain an understanding of the conditions that produce or maintain convection which may lead to severe storms.

This report will describe three mesoscale phenomena which have been observed recently by the GOES-EAST satellite. The analysis of these events is in a preliminary stage. The discussion will concentrate on a description of these cases and suggestions as to the physical factors involved, based on related studies reported in the literature.

OBJECTIVES

The immediate objective of this study has been to gain familiarity with some of the mesoscale phenomena which are observed by the GOES satellite. The ultimate objective has been to determine by direct analysis and reasonable inference the physical processes that are involved in producing these mesoscale events. This objective has been only partially satisfied at this time.

CASE 1 - MAY 17, 1982

Figure 1 shows the cloud images over Texas at 1300 GMT on May 17, 1982 as seen by the GOES-EAST satellite with 8 km resolution. Of particular interest is the roughly triangular area delineated bythe convective clouds over north, central Texas.

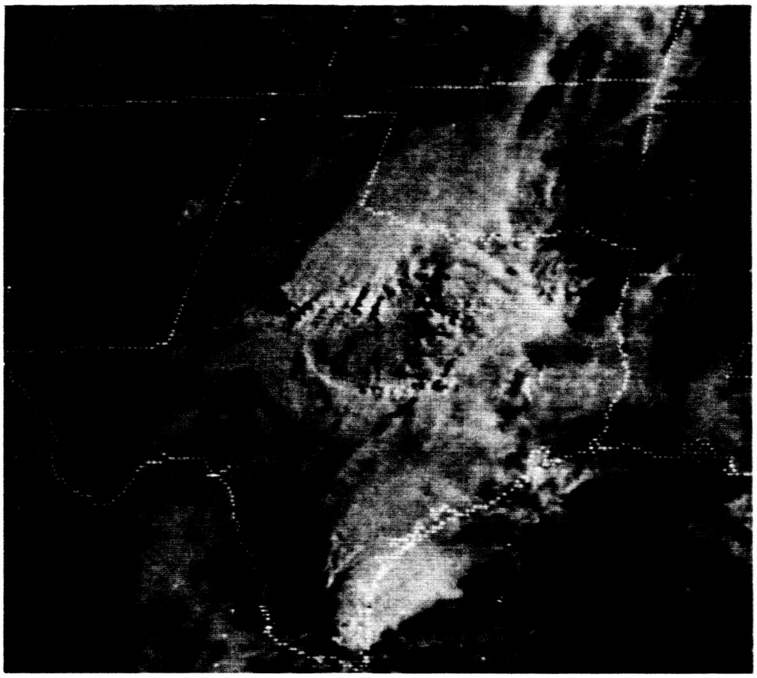

Fig. 1 GOES-EAST visible imagery at 1300 GMT, May 17, 1982 for Texas. The resolution is at 8 km.

Fig. 2 GOES-E enhanced infrared image for Texas at 1230 GMT on May 17, 1982. The resolution is at 8 km.

Figure 2 shows the enhanced infrared (IR) images at 1230 GMT for the same resolution. The MB color scheme shows some cloud tops in the cirrus shield on the northwest flank of the triangle at temperatures colder than $-58^{\circ}C$. The temperatures indicated on the eastern flank of the triangle are generally warmer than $-52^{\circ}C$, except at one point. These conditions would seem to indicate that the most intense convection was occurring just north of Abiline, TX (ABI); however, the manually digitized radar (MDR) reports show level 3 values in both areas.

The thin, curved line of cumulus clouds making up the southern side of the triangle in Fig. 1 has no temperature as cold as $-32^{\circ}C$ and is non-precipitating. The same thing is true of the clouds in the interior of the triangle. Purdom (1973, 1976) has found that this line of clouds marks the edge of a mesohigh in the surface pressure field and has called it an "arc cloud." He also found that the arc cloud is a moving boundary having many of the properties of a cold front, e.g., a wind shift, a pressure jump, and a drop in both temperature and dew point temperature. Where the moving arc cloud intersects other mesoscale boundaries such as fronts, squall lines or other arc clouds is where intense convection is most likely to occur. Also, convection is likely to be enhanced, perhaps even to the intense stage, if an arc cloud moves into a region where some convective clouds already exist (Purdom, 1979). Such was the case in southeastern Texas on this day.

Figure 3 shows the situation at 1600 GMT; the resolution in this figure is 2 km. By this time the convective area north of ABI is beginning to dissipate while that on the eastern flank of the arc cloud has intensified. The arc has expanded normal to itself in the southward direction. This process continues for the next several hours, as seen in Fig. 4 at 1930 GMT. By this time, the convective activity has ceased on the western flank of the arc and the cloud debris in the central portion of the ring has even vanished, probably as a result of substantial subsidence in this area. On the other hand strong convection has been maintained on the east and southeastern flanks of the ring.

The arc cloud for this case is still clearly delineated in deep south Texas in the visible satellite imagery at 2030 GMT (not shown here) but becomes lost to view after this time because the cirrus tops of thunderstorms in Mexico have expanded northward over southern Texas. Note in Fig. 4 that although there is no convection along the western portion of the arc cloud, the penetration of the arc into this region appears to have enhanced the growth of the cumulus cloud lying just to the north of Midland, TX. Intense convection develops northward from this point over far west Texas and eastern New Mexico over the next 8 hours.

The surface synoptic conditions for this case at 1200 GMT in the Texas region are shown in Figs. 5 and 6. The National Weather Service analysis of the pressure field has been modified and replaced with isobars drawn at a 1-mb interval in Fig. 5. Isotherms at a $2^{\circ}F$ interval appear in Fig. 6. In both analyses the reported data have been assumed to be correct and have been fully utilized. The thin line or ring with small markings like a cold front represents the estimated position of the arc cloud at this time. It is seen that higher pressure fills the interior of the ring, producing a relative trough in the pressure along the ring.

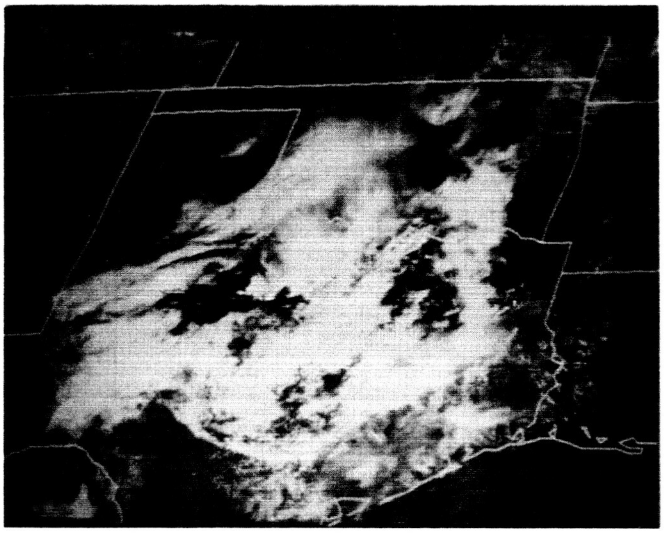

Fig. 3 GOES-EAST visible image at 1600 GMT - 2 km resolution.

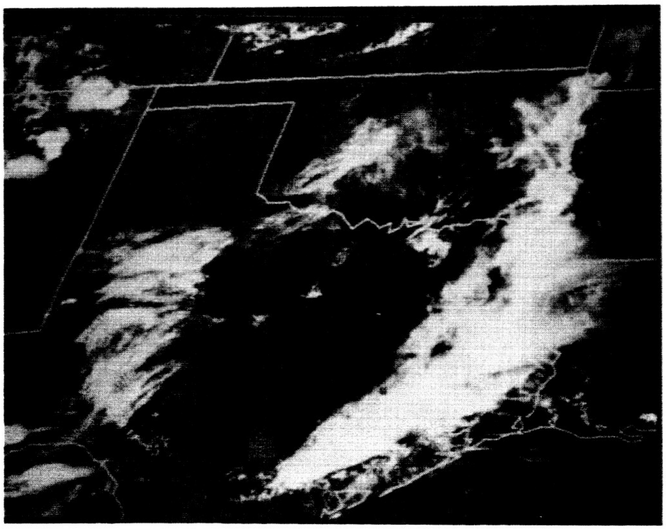

Fig. 4 GOES-EAST visible image at 1930 GMT - 2 km resolution. The two lines of crosses mark the positions of the arc cloud at 1400 and 1600 GMT.

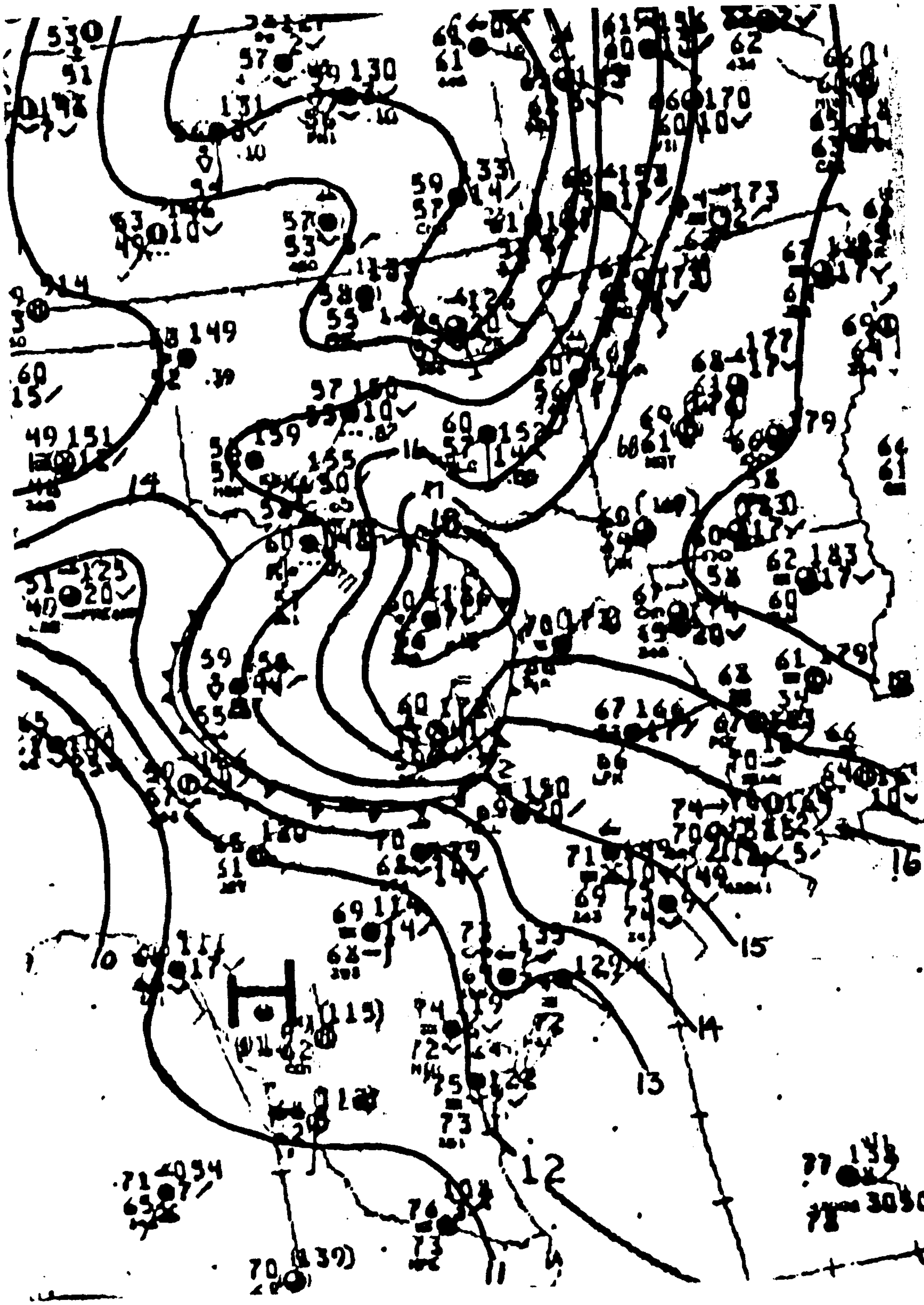

Fig. 5 A portion of the 1200 GMT surface map for 1200 GMT, May 17, 1982. The National Weather Service analysis has been replaced with isobars at 1-mb intervals. The thin line with cold front markings encloses the storm area in northern Texas at this time. A mesohigh is centered over the Dallas-Ft. Worth area.

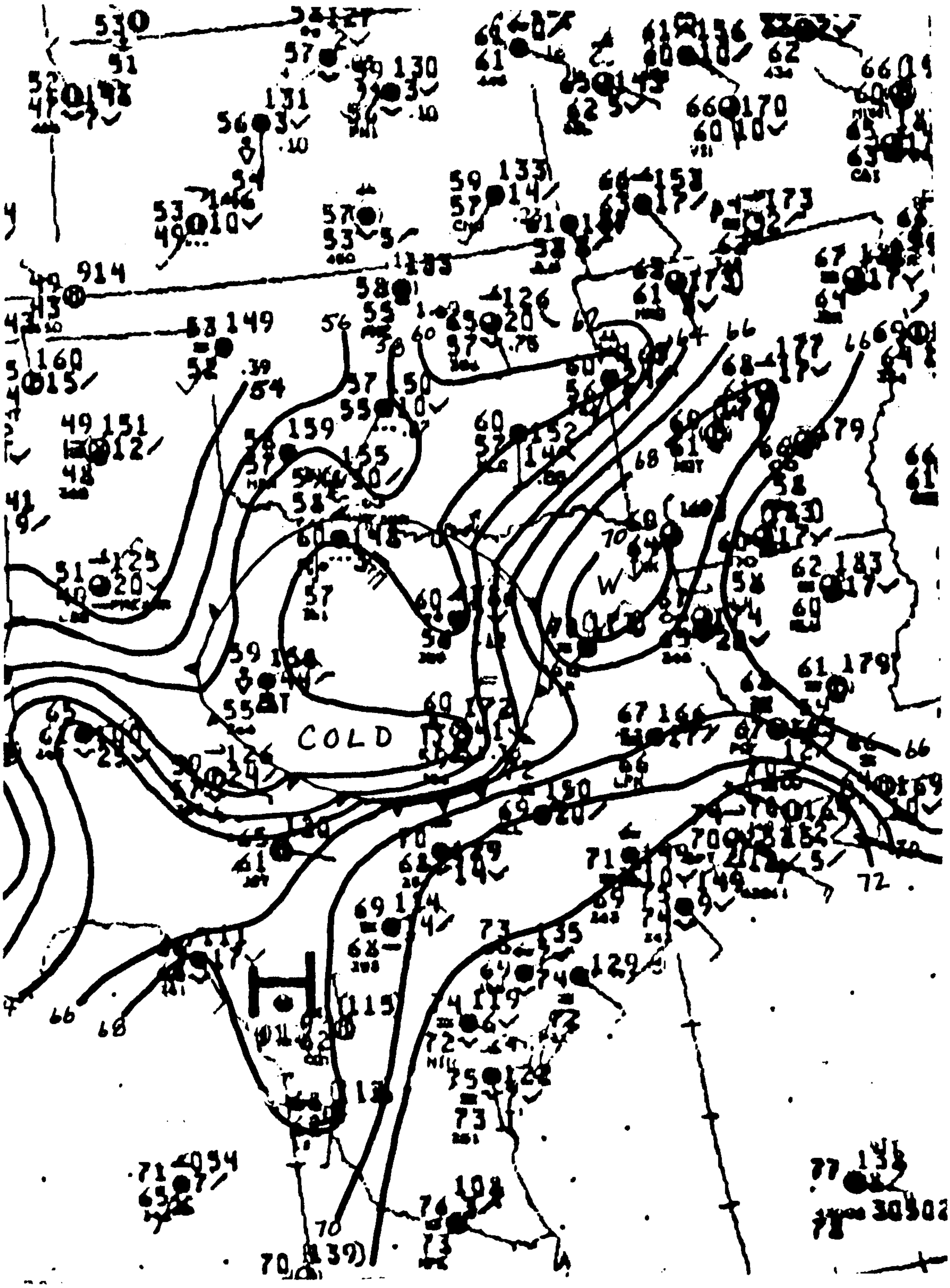

Fig. 6 The mesoscale temperature analysis at 1200 GMT, May 17, 1982. The isotherms are at 2°F intervals.

The isotherms in Fig. 6 indicate temperature gradients on the southern and eastern sides of the arc much like that of a weak cold front. This is even more pronounced in the field of equivalent potential temperature because the cooler air also has a lower dew point temperature. Both Purdom (1973, 1976, 1979) and Maddox (1981) have called attention to the mesohigh associated with large convective complexes but have not shown the coexisting temperature field. Nevertheless, a temperature field much like that in Fig. 6 could be drawn in Maddox's Fig. 5c.

It remains to be determined by future analysis of the pressure and temperature fields at subsequent times if the features seen in Figs. 5 and 6 are maintained over the next 12 hours. This will provide some clues as to the dynamics at play which maintains the identity of the arc cloud for about 12 hours and permits it to propagate a distance of about 300 km. Certainly also there is a great need to understand how the arc cloud interacts with its environment to enhance or produce new convection.

There is one other point of interest involved in this case. It can be seen in Fig. 4 that the middle and high clouds at the western end of the arc cloud have taken on a banded structure. Erickson and Whitney (1973) have reported on a satellite observation of an arc-shaped banded structure in middle clouds which extended from northeast Texas into central Arkansas. They assumed that this structure was the result of a propagating gravity wave initiated by violent thunderstorms to the northwest of the cloud bands. There are no other satellite images to confirm the conjecture that they also were dealing with an arc cloud but their description of conditions and events associated with these cloud bands makes this seem likely. This case has been examined theoretically by Ley and Peltier (1981) as an eigenvalue problem by using the wind and temperature distributions measured by upper-air soundings at Shreveport, LA and little Rock, AR. The solution mode which they found to have the least horizontal attenuation was ducted vertically, thus confining the energy. This mode also most closely matched the wavelength of the cloud bands ($\simeq$10 km) and the observed phase speed ($\simeq$12 ms^{-1}).

CASE 2 - JUNE 7, 1982

Figure 7 gives the National Weather Service analysis of a portion of the 850 mb surface at 1200 GMT on June 7, 1982. The high pressure ridge line extending from east of Hudson's Bay to Louisiana had very little tilt from the surface to the tropopause and was stationary over the next 12 hours. Therefore, the wind over West Virginia, Virginia and North Carolina was essentially free of direction shear with height.

The 1200 GMT soundings for Huntington, WV (HTS) and for Greensboro, NC (GSO) are given in Fig. 8. Subsidence inversions are evident in both soundings and the wind distribution in the boundary layer at GSO approximates the Ekman profile.

The cloud bands seen in Fig. 9 clearly must represent visual evidence of lee waves produced by the movement of the air over the Clinch and Shenendoah Mountain chains. The winds over West Virginia are essentially normal to these mountains. The sounding at HTS indicates that the most likely height of these bands is about 1 km above local average terrain

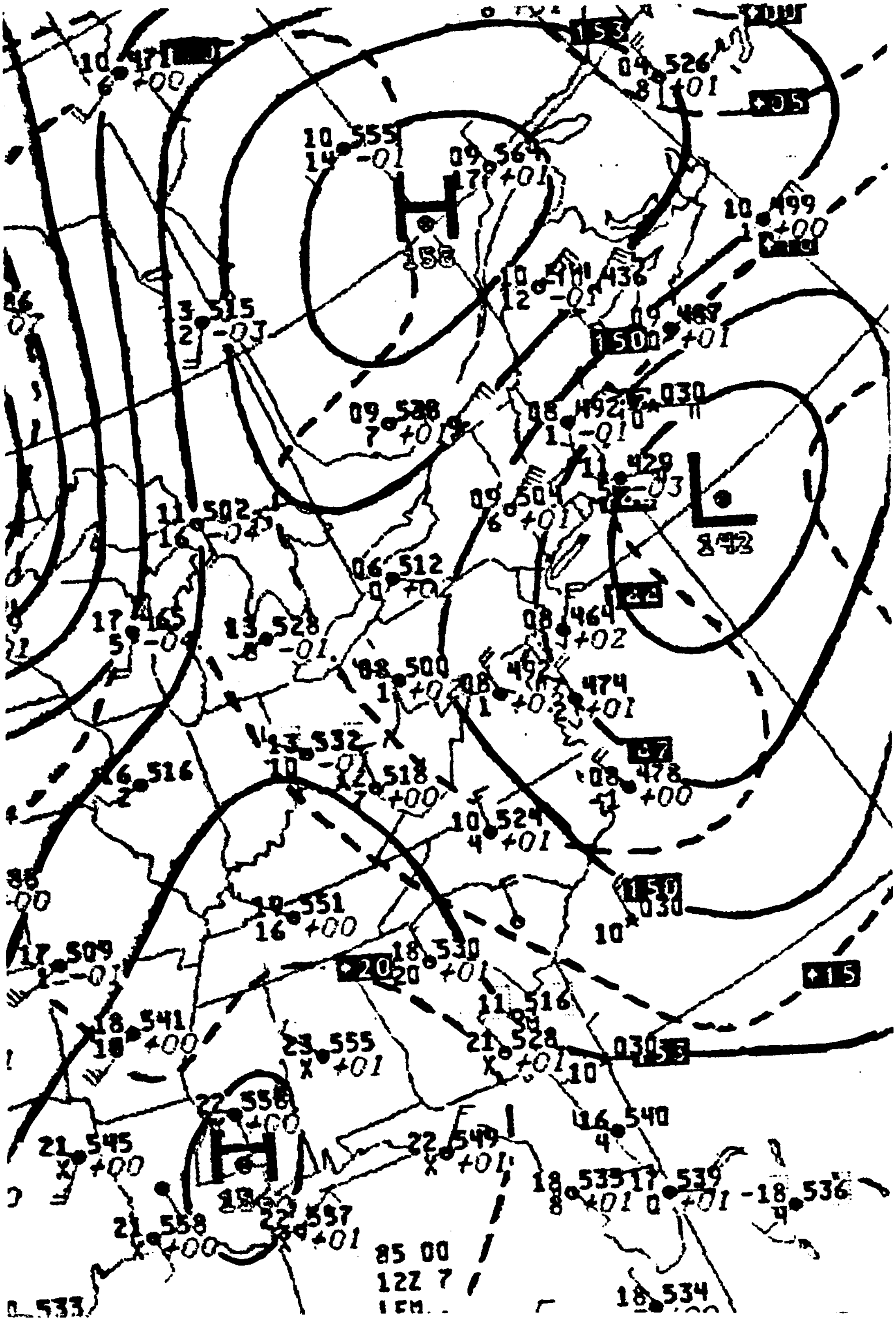

Fig. 7 The 850-mb surface analysis at 1200 GMT on June 7, 1982.

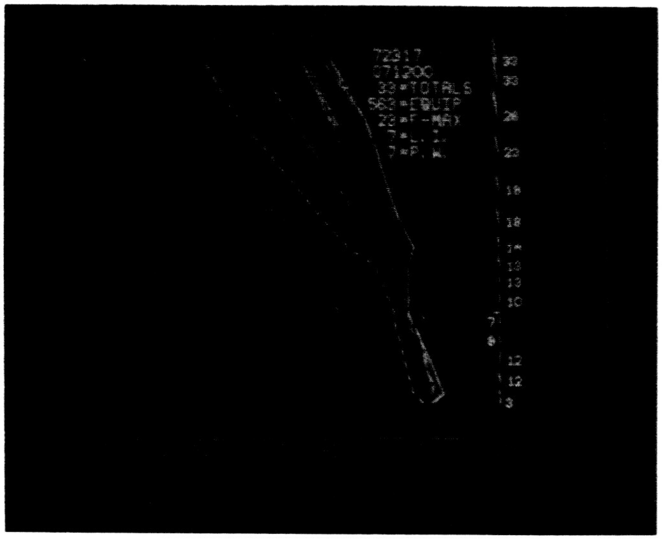

Fig. 8 Soundings at HTS and GSO for 1200 GMT, June 7, 1982.

Fig. 9 GOES-EAST visible imagery at 1330 GMT, June 7, 1982 with 1 km resolution.

height at the base of the weak subsidence inversion. The wavelength of these bands varies from 5 to 10 km and the fact that the bands are stationary, as seen in succeeding satellite images at half-hour intervals (see Figs. 10-13), indicates that the air must be moving through the clouds.

These lee-wave clouds begin to dissipate about 1500 GMT (see Figs. 12 and 13), possibly because convective circulations produced by solar heating of the surface breaks up the wave structure of the flow.

Reviews of the various theories explaining lee-wave formation have been given by Booker (1963) and Gossard and Hooke (1975). A study specifically directed to lee waves over the Blue Ridge Mountains in northern Virginia has been made by Smith (1976).

CASE 3 - JUNE 7, 1982

Figures 10-13 show the lee-wave cloud images as a function of time, as discussed above. However, starting at 1400 GMT (Fig. 10) it is seen that another banded cloud structure suddenly appears just to the west of GSO. These bands of small cumulus are oriented nearly parallel to the wind flow above the planetary boundary layer and have a spacing of about 5 km or less. During the next hour, there is a lateral spread of this pattern as new lines of clouds appear both to the east and west of the original area. The development of cumulus in the morning hours certainly was to be expected in this area, considering the conditions shown in the GSO sounding (Fig. 8). The lower troposphere was quite moist and only a small amount of solar heating at the surface was required to eliminate the shallow nocturnal inversion. The vertical growth of the clouds was suppressed by the stable layer between 830 and 730 mb.

The tendency for low-level clouds to develop in streets parallel to the flow is well-known (Kuettner and Soules, 1966; Kuettner, 1971). One explanation of this phenomena is that the convection is organized by what is referred to as Ekman-layer instability. Various theoretical studies (e.g., Barcilon, 1965; Lilly, 1966) have shown that horizontal roll vortices may develop in the planetary boundary layer (PBL) with their axis making an angle of 10^{o}-20^{o} to the left of the geostrophic wind vector. The mean flow in the PBL must veer with height in accordance with the Ekman distribution. The wind distribution in the GSO sounding at 1200 GMT veers to a height of 1212 m above sea level. These vortices have been observed in laboratory studies by Faller (1965) and in nature by Angell et al. (1968), LeMone (1973) and Berger and Doviak (1979). These studies predict that cloud streets may have a lateral spacing of 2-8 km and may be several hundred kilometers in length. They should move normal to themselves at a very slow rate, on the order of 1 ms^{-1}.

The rapid lateral spread of the cloud streets in this case may simply be a result of local variations in surface heating and/or boundary layer stability. However, this spread seemed to be smoothly continuous rather than random, as would be expected. This implies some organizing influence such as might be provided by a gravity wave.

Fig. 10 Visible imagery at 1400 GMT, June 7, 1982. Surface winds also are shown. 1 km resolution.

Fig. 11 Visible image at 1430 GMT, June 7, 1982. Lee waves normal to the wind and convective cloud streets parallel to the wind are present.

Fig. 12 Cloud images at 1500 GMT, June 7, 1982. Surface winds also are shown.

Fig. 13 Cloud images at 1630 GMT, June 7, 1 82.

Gravity waves have received considerable attention in the literature and the citations are too numerous to list here. In view of the behavior of the cloud bands or streets described above, the most pertinent article is that by Jones (1972). If gravity waves are to propagate over any significant horizontal distance, their energy must be confined in a layer. A stable layer embedded in a region of lower stability, such as existed on this day at GSO (Fig. 8), will serve as an energy duct. Jones shows that when there is a vertical shear across the stable layer, there are severe restrictions on the gravity wave modes that can be ducted and still propagate in the direction of the mean wind. These restrictions are removed as the angle between the shear vector and the propagation vector increases. Thus, ducted waves are more likely to be found propagating nearly normal to the shear vector. This should aid in establishing cloud streets parallel to the shear vector.

CONCLUSIONS AND RECOMMENDATIONS

This study has described three mesoscale systems commonly observed in the GOES-EAST imagery. Lee wave clouds and cloud streets have received much study, both through measurements and through theoretical treatment. The literature also is rich with studies dealing with gravity waves and their possible role in producing mesoscale convective bands over a broad range of wavelengths.

On the other hand, the arc cloud and its associated convective complex have received only a descriptive, mainly qualitative treatment of the sort given here. The mesohigh has been attributed to the collective effect of downdrafts and gust fronts from the individual cells making up the convective complex. Starting from this point, Maddox (1980) has attempted to explain in qualitative terms the life cycle of the mesoscale convective complex (MCC). Although his examples of the MCC appear to be very similar to Case 1 described here, there is no evidence of the arc cloud feature nor of an interaction with other convective areas.

The difficulty in developing a theory for the dynamics of the arc cloud complex (ACC) is, as stated previously, that conventional upper-air observations within the ACC generally are not available. Radar observations will not be particularly useful here because by the time the arc cloud becomes defined in the satellite imagery, apparent subsidence is clearing out the precipitation and cloud debris on the interior of the arc ring. Therefore, it is recommended that observations with the Visible and Infrared Spin-Scan Radiometer Atmospheric Sounder (VAS), now mounted on the GOES, be utilized to establish the vertical moisture and temperature distributions in the vicinity of the arc boundary. A number of cases should be studied to determine systematic conditions. A numerical modeling effort also would be useful to see if the common conditions can be simulated.

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